APPENDIX H
CULVERT ANALYSIS - PREPARED BY LOLO NATIONAL FOREST WITH REVISIONS BY RIVER DESIGN GROUP AND DEQ

This appendix includes an analysis of potential sediment risk from culvert failures as well as an analysis of fish passage capabilities of a sub-set of culvert-stream crossings in the Prospect Creek watershed. Data were collected and analyzed by Lolo National Forest with additional analysis by DEQ.

Introduction

Spatial analysis of roads and stream GIS layers indicates 307 road-stream intersections within the Prospect Creek watershed. In 2002-2003, these culverts were screened as part of a Forest-wide inventory of culvert fish passage capabilities, and a formal survey was completed at 30 crossings on fish-bearing streams. Fish-bearing streams were defined as those with intermittent or perennial flow and less than 25% gradient. Surveyed culverts represent approximately 9% of the 307 culverts in the Prospect Creek watershed. Culverts were surveyed in each of the Prospect Creek tributary watersheds (**Table H-1 and Figure H-1**). Surveyed culverts are all located on roads within the National Forest boundary or on roads outside the National Forest boundary but maintained by the Forest Service. Data collected include culvert dimensions, average fill height, road width, bankfull width, and other parameters.

Table H-1. Stream Crossing Culverts on Fish-Bearing Streams in Prospect Creek Watershed Surveyed in 2002-2003 as Part of Culvert Fish Passage Analysis

HUC 6 No. (1701021306xx)	HUC 6 Name	GIS Count	Number of Crossings Surveyed	Number of Crossings Surveyed & Included in this Analysis
05	Clear Creek	76	6	6
01	Cooper Gulch	16	6	2
03	Crow Creek	32	2	2
04	Wilkes Creek	17	0	0
06	Dry Creek	23	2	2
07	Lower Prospect	114	9	7
02	Upper Prospect	29	3	3
Prospect Creek HUC 5		**307**	**28**	**22**

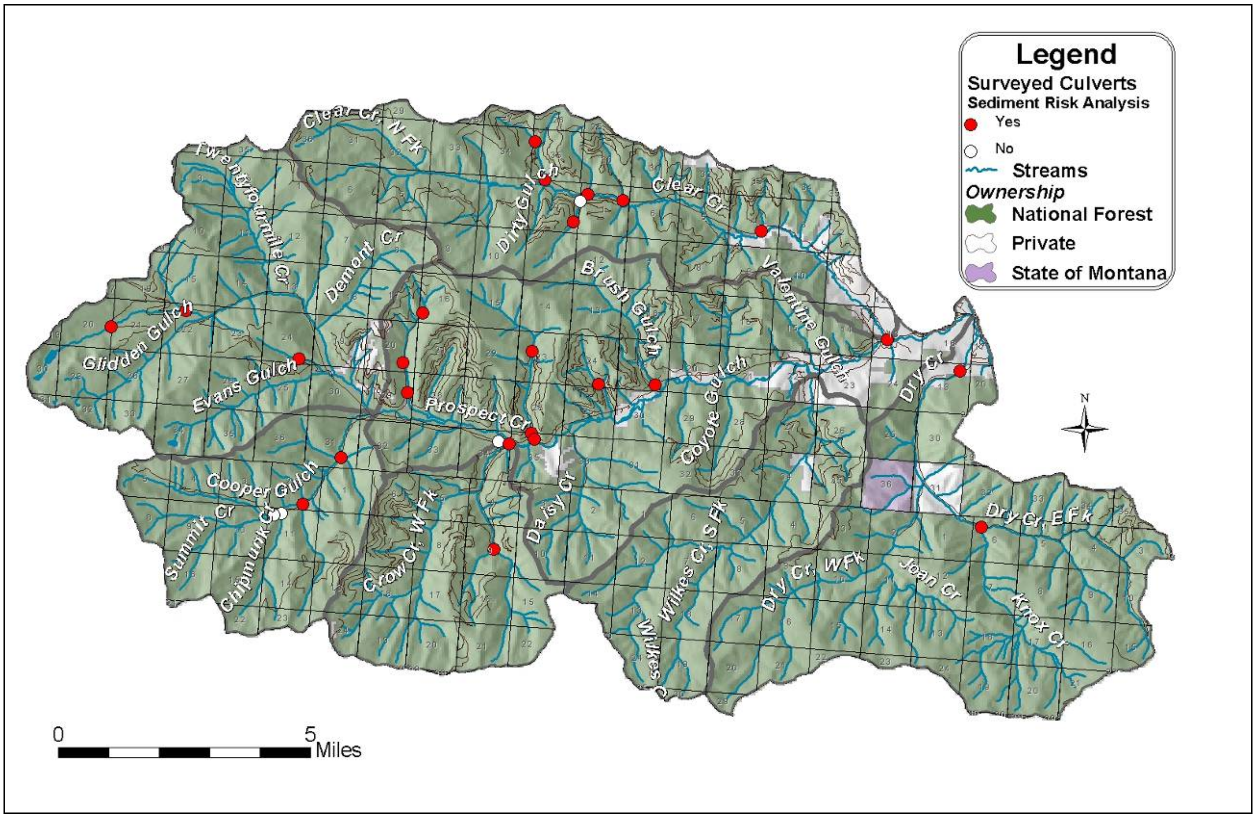

Figure H-1. Stream Crossing Culverts on Fish-Bearing Streams in Prospect Creek Watershed Surveyed in 2002-2003 as Part of Culvert Fish Passage Analysis

The culvert fish passage analysis revealed that almost all of the culverts surveyed span less than the bankfull width of the streams they cross. This relationship is expressed as a ratio of culvert width to bankfull width, also known as constriction ratio or bankfull ratio. Ninety-six percent of culverts surveyed have a constriction ratio less than 1.0 (**Figure H-2**).

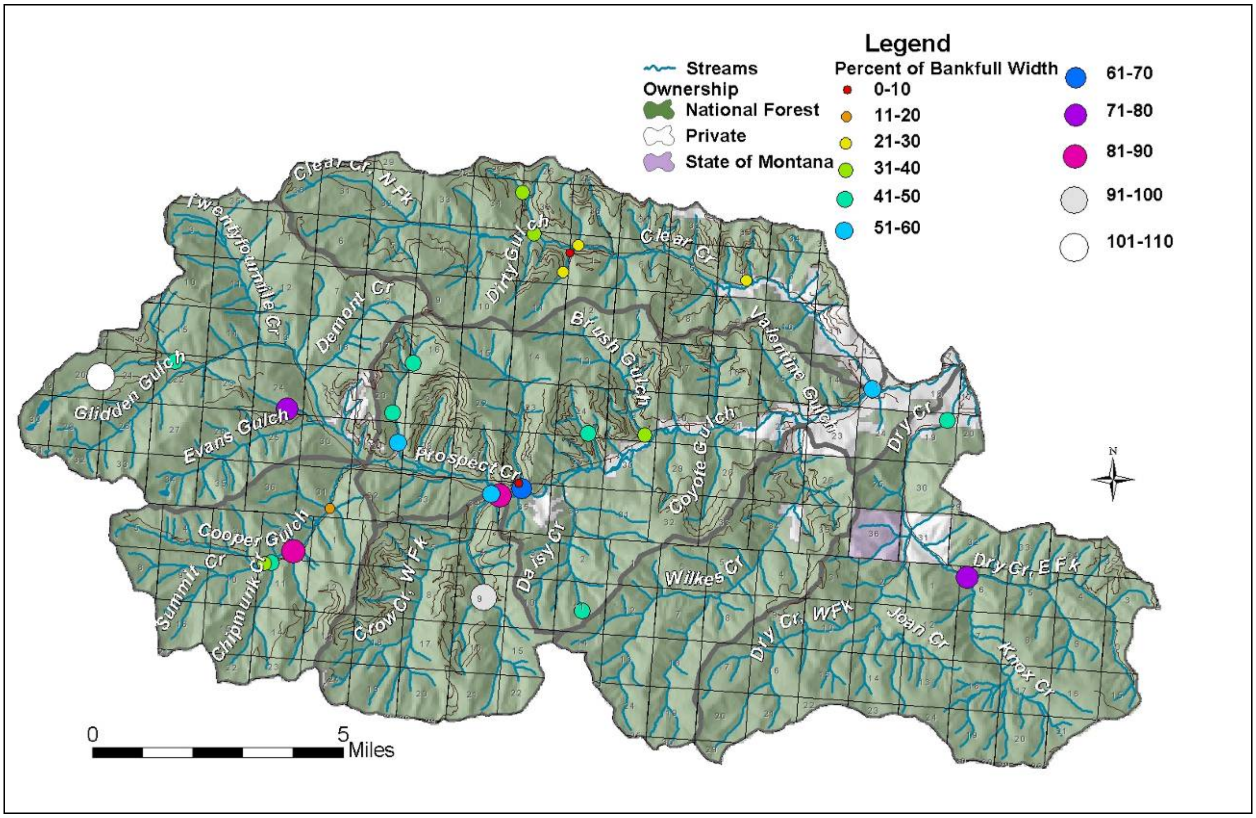

Figure H-2. Surveyed Stream Crossing Culverts by Bankfull Ratio

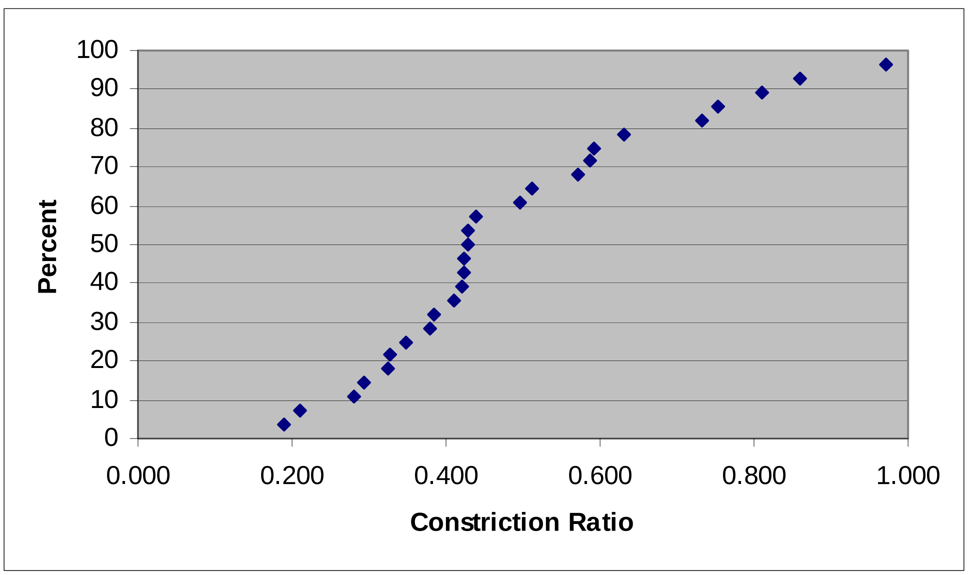

Figure H-3. Cumulative Percent Distribution of Constriction Ratio for Culverts on Fish Bearing Streams in the Prospect Creek Watershed

The ability of fish to pass through a culvert with a corrugated bottom is limited, especially when the constriction ratio is less than one. Fish passage capabilities of 28 crossings were evaluated by modeling with the culvert survey data using Region 1 Fish Passage Evaluation Criteria. Based on analysis of the culvert survey data, 2 (6.6%) of these culverts allow for passage of both adult and juvenile fish, while 27 (90%) pass neither adult nor juvenile fish. For the remaining culvert (3.3%), passage for adult fish is possible but not for juvenile fish. (**Table H-2 and Figure H-3**).

Table H-2. Fish Passage Capability Results

		Juvenile Fish Passage		
Adult Fish Passage		Green	Natural Simulation	Red
	Green	1	0	1
	Natural Simulation	0	1	0
	Red	0	0	27

Green = hydraulically possible, **Natural Simulation** = conditions are natural (bridge or bottomless arch); passage is possible, **Red** = hydraulically impossible

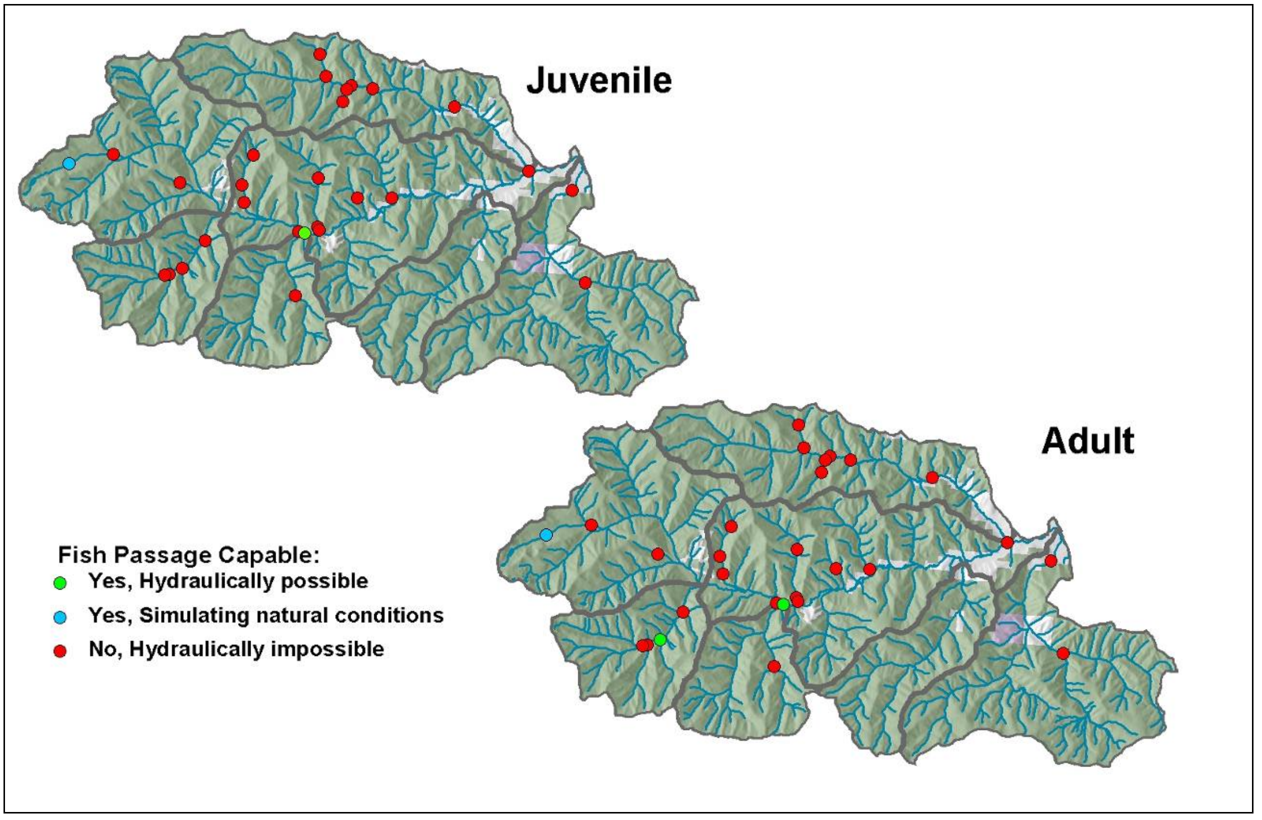

Figure H-4. Map of Fish Passage Capabilities of Surveyed Stream Crossing Culverts in the Prospect Creek Watershed

Not only do undersized culverts often restrict or prohibit fish passage, they are also a potential source of sediment as they are susceptible to failure or blow-out due to the ponding or bottleneck of water at the culvert inlet. Culvert failure results in direct contribution of road fill material to the stream. The following study determined the road fill volume subject to erosion and direct delivery from culvert failure. Modeled discharge and associated headwater depth to culvert depth ratio (Hw:D) was used to assess culvert flow capacities and failure risk. **Table H-3** contains the constriction ratios and associated road fill volume for each surveyed stream crossing.

Table H-3. Constriction Ratio and Associated Road Fill Volume for Surveyed Crossings Included in this Analysis

HUC 6 Name	Stream Crossing	Constriction Ratio	Fill Estimate*
Clear	Clear Creek	0.21	148
Clear	Looters Gulch (Prospect Creek)	0.28	72
Clear	Monroe Gulch	0.33	64
Clear	Monroe Gulch	0.35	73
Clear	Quail Gulch	0.43	30
Clear	Clear Creek	0.59	1993
Cooper	Cooper Creek, Tributary	0.19	91
Cooper	Spokane Creek	0.81	78
Crow	Crow Creek	0.86	439
Crow	Crow Creek, East Fork	0.97	401
Dry	Dry Creek	0.42	1174
Dry	Dry Creek, East Fork	0.73	54
Lower Prospect	Brush Gulch	0.38	24
Lower Prospect	Cox Gulch	0.43	62
Lower Prospect	Cox Gulch	0.50	41
Lower Prospect	Therriault Gulch	0.51	132
Lower Prospect	Cox Gulch	0.57	110
Lower Prospect	Prospect Creek, Tributary	0.59	109
Lower Prospect	Therriault Gulch	0.63	638
Upper Prospect	Prospect Creek, Tributary	0.44	83
Upper Prospect	Evans Gulch, Tributary	0.75	53
Upper Prospect	Prospect Creek	1.06	343
*Assumes 1yd3 = 1 ton.			

Total road fill failure is not always the response to ponded water at the inlet of undersized culverts. In some instances, only part of the road fill may be contributed to the stream as a result of culvert failure. In other cases, culvert failure occurs when ponded water overflows onto the road causing erosion of the road surface.

Methods

The magnitude of peak discharge (Q) for the 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals was modeled for each surveyed stream crossing culvert using regression equations developed by Omang (1992). Independent variables in the equations are drainage area (square miles) and mean annual precipitation (inches). Drainage area above each stream crossing was determined using a digital elevation model (DEM) in ArcMap 8.1 Hydrology Tools (ESRI, 2001). Mean annual precipitation for the area drained by each surveyed stream crossing culvert was derived from a GIS raster layer of precipitation (Daly and Taylor, 1998).

Headwater depths (Hw, depth of water ponded at culvert inlet) were determined using software from the US Department of Transportation, Federal Highway Administration (FHWA). The program HDS5eq.exe was downloaded from FHWA’s Hydraulic Engineering Software Archive website (FHWA, 2001). HDS5eq.exe is a nomograph calculator for FHWA “Hydraulic Design of Highway Culverts” (HDS-5) which uses the nomograph charts in HDS-5 Appendix D and inlet control equations found in HDS-5 Appendix A. Based on culvert material, shape, mitering, height, width, discharge, and/or culvert slope, the headwater depth of each culvert was calculated for each modeled discharge.

Analysis of sediment risk from culvert failure was completed for 24 of the surveyed crossing culverts. (Due to incomplete data or double culvert scenarios, 6 of the 30 surveyed culverts were not included in the sediment risk analysis). Modeled discharge, headwater depth to culvert depth ratio (Hw:D), and road fill volume subject to erosion should culvert failure occur were evaluated to determine sediment at risk. If the Hw:D exceeded the recommended Hw:D for a given modeled Q at a particular culvert, the associated road fill volume estimate was counted as a potential sediment contribution. Culverts with Hw:D greater than 1.4 (ponding to the top of the culvert inlet) were considered at risk of failure due to the forces of ponded water at the culvert inlet. It should be noted that culvert failure does not occur every time Hw:D exceeds 1.4. However, corrugated steel pipe manufacturers recommend a Hw:D maximum of 1.5 (ponding 50% above the top of the culvert), and if at all possible less than or equal to 1.0 (American Iron and Steel Institute, 1994). In this analysis, a maximum Hw:D of 1.4 was considered. Culverts capable of passing a given discharge without exceeding Hw:D = 1.4 were considered not at risk to failure and therefore the potential sediment contribution was 0.

Table H-4. Percent of Culverts Surveyed Capable of Passing Flows with HW:D ≤ 1.4

	Hw:Depth	
	< 1.4	**>1.4***
Q2	100	0
Q5	100	0
Q10	92	8
Q25	92	8
Q50	83	17
Q100	75	25

* % of culverts not meeting HW:D <1.4 criteria

Results

As modeled discharge increases, so does the number of culverts incapable of passing the greater discharges. All surveyed culverts evaluated are capable of passing the Q2 discharge with a Hw:D equal to or less than 1.4, while 25% cannot pass Q100 with Hw:D equal to or less than 1.4 (**Table H-4 and Figure H-5**).

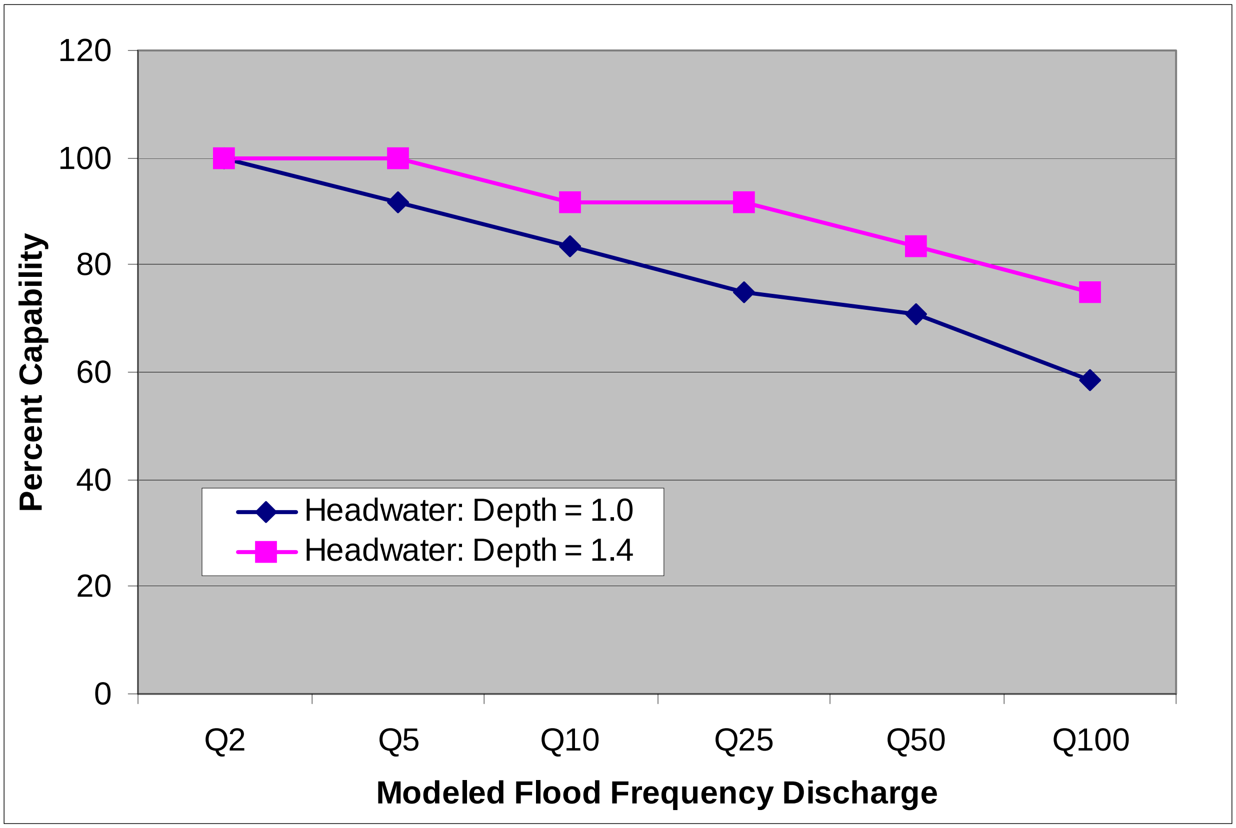

Figure H-5. Percent of Culverts Surveyed Capable of Passing Flows

Potential sediment associated with culvert failure was summarized by HUC 6 under each modeled discharge - headwater to depth ratio combination (**Table H-5**). For the Prospect Creek HUC 5, total potential sediment in a single year ranges from 0 tons for Q2 and Hw:D $\leq$ 1.4 to 1430 tons for Q100 and Hw:D $\leq$ 1.4.

Among the HUC 6 tributary watersheds, distribution of potential sediment from culvert failure is not directly related to the distribution of culverts surveyed. Seven percent (2) of the culverts surveyed are located in the Dry Creek HUC 6 (**Figure H-5**), and account for 90% of the potential sediment from culvert failures in the Prospect Creek HUC 5 at Q100. The remaining potential sediment from culvert failures at Q100 flows respectively is in Clear and Lower Prospect Creek HUC 6 watersheds (**Figure H-6**).

Table H-5. Potential Sediment Contribution (Road Fill Estimate, Tons) at Risk from Culvert Failures Based on Modeled Discharge and Headwater Depth to Culvert Depth Ratio

	Q2	**Q5**	**Q10**	**Q25**	**Q50**	**Q100**
Headwater: Depth	1.4	1.4	1.4	1.4	1.4	1.4
Clear	0	0	0	0	0	136
Cooper	0	0	0	0	0	0

Table H-5. Potential Sediment Contribution (Road Fill Estimate, Tons) at Risk from Culvert Failures Based on Modeled Discharge and Headwater Depth to Culvert Depth Ratio

	Q2	Q5	Q10	Q25	Q50	Q100
Crow	0	0	0	0	0	0
Wilkes	0	0	0	0	0	0
Dry	0	0	1174	1174	1228	1228
Lower Prospect	0	0	24	24	66	66
Upper Prospect	0	0	0	0	0	0
Prospect Creek (HUC 5)	0	0	1199	1199	1294	1430

Numbers Represent Contribution from Surveyed Crossings Only

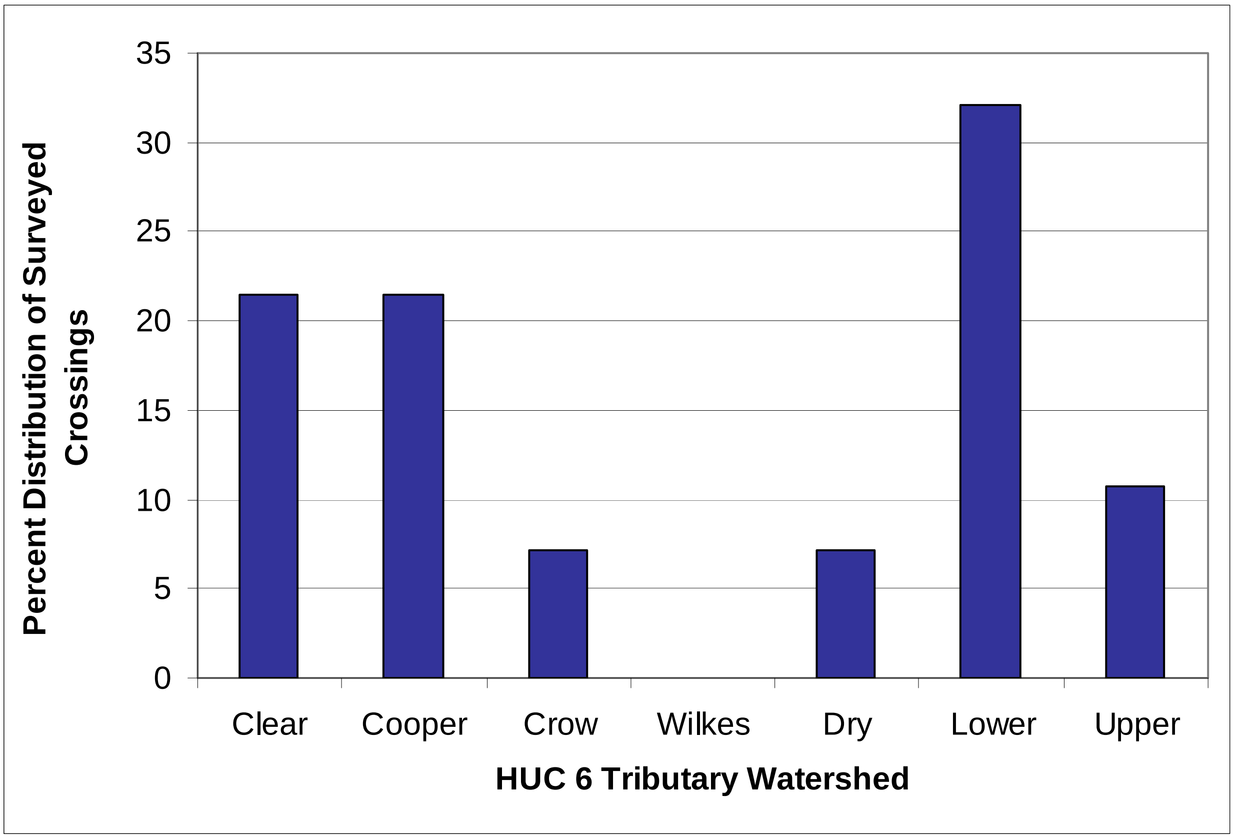

Figure H-6. Distribution Among HUC 6 Tributary Watersheds of all Culverts Surveyed in the Prospect Creek HUC 5

Estimating potential sediment contribution from culvert failure involved determining how much sediment is produced over one hundred years based on flow recurrence probability and the potential sediment load produced by each flow event, and then averaging the loads to provide the potential yearly estimated load. Additionally, it is assumed that not all of the fill at a crossing will enter the stream. An estimated 25% of road fill at an average culvert stream crossing is assumed to contribute to the sediment load in the Prospect Creek watershed under conditions where Hw:D > 1.4.

The existing culvert failure rate scenario assumes that once a failure occurs the culverts are replaced with the same size (**Table H-5**). The sediment yields from the monitored locations were then extrapolated to the watershed scale (total # of culverts identified through GIS exercise). Culvert failure modeling scenarios were completed to assist in TMDL allocations (**Table H-5**). To determine the appropriate reduction, a scenario was completed by simulating the load if all culverts were upgraded to the Q100 design. This scenario follows the guidance from the USFS Infish recommendations which calls for all culverts on USFS land to be able to pass the Q100 flow event.

Discussion

It is acknowledged that it is not reasonable to expect all culverts to be replaced with a Q100 design immediately and that upgrades will have to occur over time. However, two primary approaches exist to reduce a substantial portion of the risk of potential sediment contribution from culvert failure. One approach is to upgrade all culverts incapable of passing the most frequent flows, or have the most likely potential to fail in the near future. Risk of culvert failure decreases when culverts are capable of regularly passing the most frequent flows, and some larger flows. Another approach is to target those undersized culverts with the greatest amount of road fill at risk in the event of culvert failure. By ensuring that culverts with the greatest amount of road fill are large enough to pass flows, the quantity of potential sediment decreases. The results of this analysis are based on conditions at the time of the study (2003) and do not factor in potential increased flows after timber harvest or forest fires.

In Prospect Creek, both approaches apply to the same culverts. The greatest opportunity for reducing sediment potential under the most frequent flows is in Dry Creek, and is also associated with the largest road fills at risk. The two culverts surveyed in Dry Creek account for 98% of the potential sediment from culvert failure at Q25. Upgrading these undersized culverts to meet at least Q25 would reduce the sediment potential from culvert failure under those conditions by 1174 tons (98% of 1199 tons).

For the purposes of sediment TMDL, an average annual sediment contribution from culvert failure should be determined. One approach to making this determination would be to distribute a portion of the road fill volume at risk in any given year based on recurrence intervals and the likelihood of each event occurring in a given year. The analysis period for this example is 100 years and will use the road fill volumes at risk from **Table H-5** for Hw:D of 1.4.

At the Hw:D of 1.4, the occurrence of a Q2 or Q5 does not put any road fill volume at risk of failure; the occurrence of a Q10 event puts 1,199 tons of fill at risk of failure; as does a Q25 event; and so on (**Table H-5**). The road fill volume at risk under a certain event would include the volume at risk for all smaller events. The occurrence of a Q50 event only increases the load at risk by 95 tons based on1,294 tons minus the 1,199 tons subject to failure under the Q25 and smaller events, (1,294 – 1,199 = 95), and the occurrence of a Q25 event would not increase the load at risk above and beyond that load already at risk from a 10 year event (1,199 – 1199 = 0).

This is because all culverts assessed that could pass a 10 year event with Hw:D > 1.4 could also pass a 25 year event using the same criteria.

In 100 years, a Q2 or greater flow event is likely to occur every two years or 50% of the time. Likewise, a Q5 or greater event is likely to occur every 5 years or 20% of those 100 years, and a Q10 or greater event every 10 years or 10% of the time, and so on. For a Q2 and Q5 event, 0 tons is multiplied by 50 (0 tons); for a Q10 event 1,199 tons is multiplied by 10 (11,990 tons); for Q25, 0 tons is multiplied by 4 (0 tons); and so on. Volume of fill at risk of failure is calculated in this way for each recurrence interval (**Table H-6**). By adding the product values calculated in this way for each recurrence interval, the resulting sum is the volume of fill at risk of failure that is contributed to the stream network over 100 years by the 8% sub-sample of culverts (**Table H-6**).

For the Q100 upgrade scenarios, culvert failure from storm events below the upgrade condition is assumed to occur once before being replaced with the appropriate sized culvert. To determine the fill contributed from these failures, failure at culverts less than the Q100 design is then assumed to occur once, plus an additional time where one failure is likely to occur over 100 years, or a Q100+ event. In this case, the load at risk associated with all culverts less than a Q100 design is 1294 tons. Assuming these all fail once and are then upgraded, this load (1294) is added to the load at risk associated with Q100 failure (1294+136=1430). The total load is then the sum of pre and post upgrade loads (1294+1430=2724).

Table H-6. Cumulative 100 Year Sediment Load Associated with Surveyed Culverts and for Q100 Upgrade Scenario

Q	No Upgrade After Initial Failure	Upgrade to Q100 After Initial Failure
2	0	0
5	0	0
10	11,990	1,199
25	0	0
50	190	95
100	136	1,430
Load (Tons/100 Years)	**12,316**	**2,724**

These results are for the inventoried culverts only. Based on the information in **Table H-1**, the inventoried culverts represent a sub-sample of approximately 8% of the total stream crossing population of 307 crossings.

In order to determine the potential annual sediment load from culvert failure that could occur in the Prospect Creek Watershed, the values associated with the assessed culverts must be extrapolated to all culverts in the watershed. Average annual load per culvert was determined and applied to each culvert for the two culvert condition scenarios (**Table H-7**). The average load per culvert was then applied to the number of culverts within each subwatershed to determine the average annual load per stream from culvert failure (**Table H-8**).

Table H-7. Extrapolition to all Prospect Creek Watershed Culvert

Scenario	Surveyed Culverts	All Culverts	Delivery Factor (0.25)	Avg Annual Load	Avg Load Per Culvert
No upgrade	12,316 ton/100 year	157,546	39,387	394	1.3
Q100 Upgrade	2724 ton/100 year	34,845	8,711	87	0.3

Table H-8. Average Annual Load by Sub-Watershed

Sub-Watershed	# of Culverts	No Upgrade	Q100
Clear	76	99	23
Cooper	16	21	5
Crow	32	42	10
Wilkes	17	22	5
Dry	23	30	7
Upper	114	148	34

Several caveats should be considered when interpreting this analysis. First, the USGS regression equations are subject to large standard errors that at times can substantially over or under predict discharge. Second, the assessment was conducted using a sub-sample of culverts in the Prospect Creek watershed. Because of the relatively small sample size, the entire population of analyzed culverts was used to extrapolate across the Prospect Creek watershed, rather than analyzed culverts from a subwatershed representing that particular subwatershed. It is assumed that all road crossings are managed similarly throughout the Prospect Creek watershed. The sub-sample of culverts used (fish-bearing streams) is biased toward stream crossings on wider, lower gradient streams, with greater discharges (hence the likelihood of bearing fish). The unsampled population of culverts typically occurs on narrower streams with steeper gradients and perhaps smaller discharges, and with larger road fills and smaller diameter culverts. Road fill volume also varies according to stream size and hillslope gradient.

Another important fact to consider is that the load associated with a Q100 design assumes failure at the Q100 flow, yet the desired scenario is that all culverts are upgraded to the Q100 flow design. This then implies that even if the Q100 design criteria is met, all culverts will fail at that flow. However, the recurrence interval “Q100” simply means the flow associated with the Q100 flow event, *or greater*, is likely to occur once in 100 years. Realistically, culvert design to meet the Q100 flow or better is the optimal condition short of constructing a free-span bridge. Large scale flow events that occur once per 100 years however are unpredictable and may be well beyond the Q100 flow. Therefore, even though the culverts are upgraded to meet the Q100 design flow, which is a static value, the actual Q100 event could well exceed the capacity for that design and thereby the loads associated with those culverts would still be at risk. Nevertheless, meeting the Q100 design criteria drastically reduces the sediment load that would be attributed to culvert failure in the watershed, Also important to consider is the short-term sediment contribution that results from disturbing the existing roadbed to remove and replace undersized culverts with larger culverts. Based on previous Lolo National Forest Monitoring Reports and other research the short-term sediment pulse is expected to be about 2 tons per culvert during the first 24 hours during and after culvert replacement (USDA, 1999). Most of the sediment increases passes within 24 hours, and decays to near normal levels within one year. Mitigation measures such as diverting live water, using filter cloths, slash filter windrows, and straw bales, and seeding and fertilizing can reduce this sediment increase up to 80 percent (Wasniewski, 1994).

Based on the culvert-failure analysis and extrapolation presented, the risk of sediment contribution potential culvert failures can be reduced. The restoration objective is to, at a minimum, upgrade all culverts to meet Q100 with Hw:D of less than 1.4.

After meeting Q100 capabilities, load at risk would increase with the addition of new stream crossings and/or replacement of existing stream crossings that are undersized for any flow. These situations and resulting recommendations are addressed in the allocations and implementation sections of this document (**Sections 6.0 and 8.0**). If new undersized crossings are established then existing undersized crossings should be upgraded or removed to equally compensate for the increase in road fill at risk from the new crossing structure.

Consideration in culvert sizing must also be given to fish passage, the geomorphic effects such structures have on stream channels including sediment load (bank erosion and channel scour) and effects to fish habitat.

REFERENCES

American Iron and Steel Institute. 1994. Handbook of Steel Drainage & Highway Construction Products. Fifth ed. Washington D.C.: American Iron and Steel Institute.

Daly, C. and G.Taylor. 1998. Montana Average Annual Precipitation, 1961-1990. (PRISM). Corvallis, OR: Oregon State University http://nris.mt.gov/nsdi/nris/shape/precip.zip. http://nris.state.mt.us/nsdi/nris/precip.html

Environmental Systems Research Institute . 2001. ArcMap 8.1. Redlands, CA: Environmental Systems Research Institute.

Federal Highway Administration. 2001. HY 8 - HDS 5 Appendix D Chart Calculator. www.fhwa.dot.gov/BRIDGE/hydsofta.htm

Omang, R.J., 1992. Analysis of the Magnitude and Frequency of Floods and the Peak-Flow Gaging Network in Montana. *U.S. Geological Survey Water-Resources Investigations Report*: 92-4048

U.S. Forest Service. 2003. Region 1 Fish Passage Evaluation Criteria. Northern Region. Missoula, MT: U.S. Forest Service.

U.S. Forest Service. 1999. Forest Plan Monitoring and Evaluation Report. Missoula, MT: Lolo National Forest.

Wasniewski, L. 1994. Hillslope Sediment Routing Below New Forest Roads in Central Idaho. MS thesis. Oregon State University.